# Risk assessment for an Italian road network due to an extreme earthquake hazard scenario and the associated landslide cascading effects

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ABSTRACT: Natural hazards, such as earthquakes, have the potential to cause damage to transport infrastructure networks and can lead to significant network disruption and associated losses. The INFRARISK project (*Novel Indicators for Identifying Critical INFRAstructure at RISK from Natural Hazards*) is developing methodologies to assess the impact of extreme natural hazard events on critical transport infrastructure networks. To demonstrate the systematic application of the proposed methodologies, a road network in Northern Italy is being assessed due to an extreme earthquake hazard scenario and the associated landslide cascading effects. The road network is distributed over an area of approximately 990km$^2$ and is located along the Scandinavian-Mediterranean corridor of the TEN-T network, which is considered a vital axis for the European economy. The vulnerability of the road network is assessed according to the seismic vulnerability of the 340 bridges and 30 tunnels located along the network, as well as the vulnerability of 870 km of roads to earthquake-triggered landslide hazards. This paper presents the initial results of the risk assessment, which evaluates the direct consequences to the road network due to an extreme seismic hazard scenario. The methodology also supports the quantification of indirect consequences for transport networks due to natural hazard scenarios, which is the subject of future work.

KEY WORDS: Transport networks; Risk assessment; Seismic hazard; Landslide hazard.

## 1 INTRODUCTION

Transport infrastructure is critical to the effective functioning of societies. However, extreme seismic events can cause severe disruption to infrastructure networks due to the physical damage that occurs, resulting in additional travel times for network users and associated economic losses. For example, the 6.8 magnitude Northridge earthquake in 1994 significantly impacted the regional transportation system in the area of Los Angeles, California, and generated a year's worth of highway repair work as a result of the single event [1]. In Europe, the magnitude 6.3 earthquake that occurred in L'Aquila, Italy in 2009 caused transport disruption due to bridge damage and road blockages [2].

The INFRARISK project *(Novel Indicators for Identifying Critical INFRAstructure at RISK from Natural Hazards*) is developing methodologies to assess the impact of extreme, low probability natural hazard events on critical transport infrastructure networks (http://www.infrarisk-fp7.eu/). The project is focused on the TEN-T road and rail networks, which comprise the core European transport network corridors, and are critical to the effective functioning of the European economy. The objective of the INFRARISK project is to enable infrastructure managers and owners to perform stress tests for critical networks to determine their resilience to low probability, extreme natural hazard events and, consequently, to assist in the decision making process with regard to the protection of critical infrastructure networks.

As part of the INFRARISK project, the developed methodologies are being applied to selected European case studies to demonstrate the systematic application and feasibility of the proposed methodologies [3]. This paper presents one of the INFRARISK case studies, which assesses the risk of an extreme seismic hazard scenario and the associated cascading effects in terms of earthquake-triggered landslides for a road network in Northern Italy. Initial results are presented herein in terms of the cost associated with restoring the network to the level of service that existed prior to the natural hazard event, i.e. the direct consequences. The adopted methodology also considers the associated indirect consequences, relating to the additional travel times encountered by road users and the resulting economic losses, which is the subject of future work.

## 2 BACKGROUND

Seismic risk assessment for distributed transport networks generally involves the use of probabilistic methods to quantify the uncertainty associated with the ground motion intensities and the network structural damage [4] [5]. Furthermore, seismic loss estimation for distributed networks necessitates the consideration of spatially correlated ground motions for individual earthquake scenarios [6] [7].

Probabilistic methods have been employed to assess the seismic risk for highway networks, whereby the seismic vulnerability of the network bridges are characterised according to fragility curves [8] and the consequences were quantified in terms of network disruption [9]. Furthermore, the consequences of seismic hazard scenarios for road networks have been quantified in terms of the additional travel times encountered by road users [10] and the accessibility disruption for local communities [11].

The risk to distributed networks due to earthquake hazards has also been addressed in recent European-funded projects.

For example, the RISK-UE project described a general methodology to assess the seismic risk to lifeline systems and proposed mitigation strategies [12]. Likewise, the SYNER-G project assessed the seismic risk to infrastructure networks. The consequences were assessed in terms of the associated losses for critical facilities [13], and the interaction between damaged infrastructure networks and the damaged built environment was examined as part of the seismic risk analysis [14]. In this study, a probabilistic seismic risk assessment process is employed, which considers cascading effects in terms of earthquake-triggered landslides and is focused on low probability, extreme earthquake hazard scenarios.

## 3 ITALIAN ROAD NETWORK

To demonstrate the systematic application of the proposed INFRARISK methodology, a road network in the vicinity of the city of Bologna in Northern Italy was examined. The network forms part of the European TEN-T road network, specifically along the Scandinavian-Mediterranean corridor, which is considered a vital axis for the European economy. This road network is located in a seismically active region (Figure 1), which is also prone to landslides (Figure 2). Consequently, the impacts of an extreme earthquake hazard scenario and the associated cascading effects in terms of earthquake-triggered landslides were analysed for the selected road network.

## 4 METHODOLOGY

The proposed INFRARISK stress testing framework [17] requires an estimation of the risk to critical networks due to the associated hazards. To do so, a quantitative probabilistic risk assessment procedure was adopted for the selected Italian road network due to an extreme seismic hazard scenario and the associated landslide cascading effects.

### *4.1 Spatial Boundaries*

The selected Italian road network is located in the Emilia Romagna region and is distributed over an area of approximately 990km$^2$ in the vicinity of the city of Bologna. Along this network, 340 bridges (excluding culverts) and 40 tunnels were identified. The geographical location of the bridges and tunnels was obtained from Open Street Map (http://download.geofabrik.de/), as illustrated in Figure 3.

### *4.2 Seismic Hazard Scenario*

To consider a low probability earthquake hazard scenario, a Monte Carlo simulation (MCS) method was employed [18]. MCS is commonly adopted when dealing with low probability ground motions as it facilities the identification of seismic events that contribute most to target amplitude levels, and provides a powerful and flexible means for considering the uncertainties associated with the prediction of seismic ground motions, providing a clear link with the probabilistic risk analysis [19].

Based on this approach, ground-motion scenarios in terms of peak ground acceleration (PGA) were developed for selected probability levels, and a specific extreme value threshold at a reference site. These ground-motion scenarios were linked to a critical element along the road network, which was selected based on the network functionality. To identify the critical network element, a betweenness centrality method was adopted, which is used to identify the structural elements that would result in a substantial decrease in the serviceability of the network due to their failure [20].

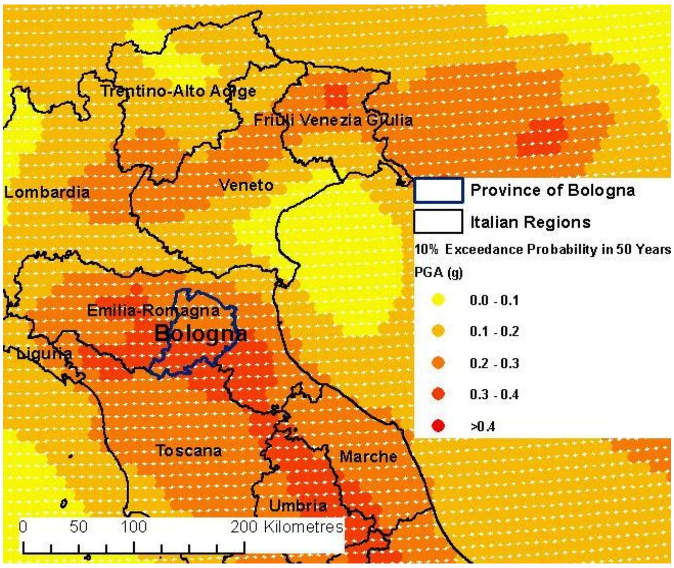


Figure 1. Peak ground acceleration (g) with a 10% exceedance probability in 50 years [15]

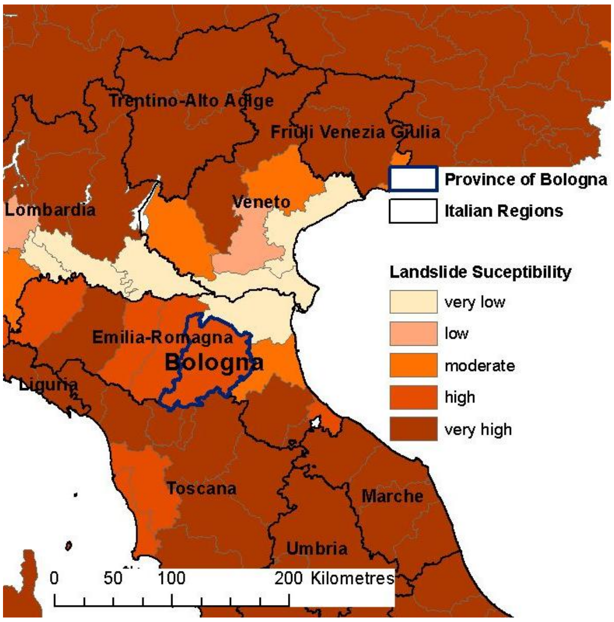


Figure 2. Susceptibility of Northern Italy to landslide hazards [16]

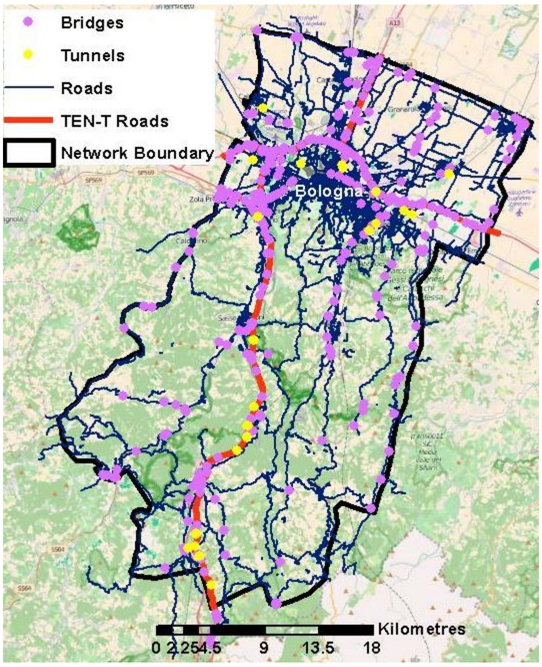


Figure 3. Italian road network

### 4.3 *Landslide Susceptibility*

The risk of the associated cascading effects in terms of earthquake-triggered landslides was also considered for the Italian road network. To assess the susceptibility of the network region to earthquake-triggered landslides, landslide yield acceleration values ($k_y$) were calculated, which indicate the horizontal acceleration that results in the initiation of sliding of the slope. Values of $k_y$ were calculated for the case study region based on geological information and a 10m resolution Digital Elevation Model, according to a sliding block displacement approach [21] (Figure 4).

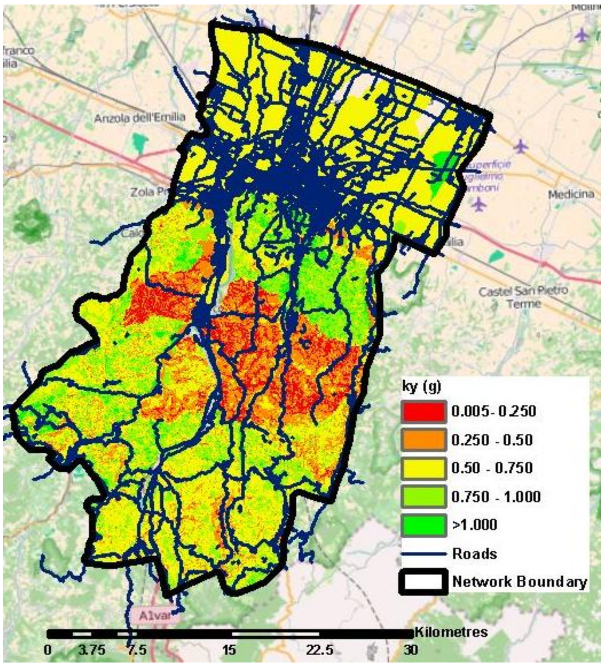


Figure 4. Landslide susceptibility

### 4.4 *Structural Vulnerability*

To estimate the seismic risk to the road network, the vulnerability of the network bridges and tunnels to seismic loading was assessed. Additionally, the vulnerability of individual road sections to earthquake-triggered landslides was assessed. To do so, fragility curves were assigned to the network elements (i.e. bridges, tunnels and road sections). Fragility curves provide the probability of reaching or exceeding specified damage states according to a measure of ground motion intensity and are represented according to Equation 1:

$$P(DS \geq ds | IM) = \phi\left(\frac{\log IM - \log \alpha}{\beta}\right) \qquad (1)$$

where *ds* is a damage state threshold of interest for a particular structure, α and β are the mean and logarithmic standard deviation of the fragility curve respectively, and ϕ is a standard normal cumulative distribution function.

For large transport networks, it is not feasible to derive fragility curves for individual structures and, therefore, fragility curves were assigned based on structural features and defined typologies [21]. For each bridge along the road network, the following structural data was gathered according to a visual inspection using Google Earth: primary material, secondary material, type of deck, width and length of deck, deck structural system, pier to deck connection, type of pier to deck connection, number of piers per column, type of section of the pier, height of the pier, number and length of spans, type of connection to the abutments, skew angle, bridge configuration, foundation type and seismic design level. A database of bridge fragility curves [22] was subsequently used to assign fragility curves based on each of the bridge typologies, as determined according to taxonomy parameters. Where multiple fragilities curves were available for a given bridge typologies, median fragility curves were estimated along with their 16% and 84% confidence bounds to account for the associated epistemic uncertainties (Figure 5). A similar approach was adopted for the identified network tunnels based on the following structural information: construction method, shape, depth, geological conditions, supporting system, and a database of tunnel fragility curves [23]. For both bridges and tunnels, the fragility curves were defined in terms of four damage states (ds): 1) Slight, 2) Moderate, 3) Extensive, and 4) Complete.

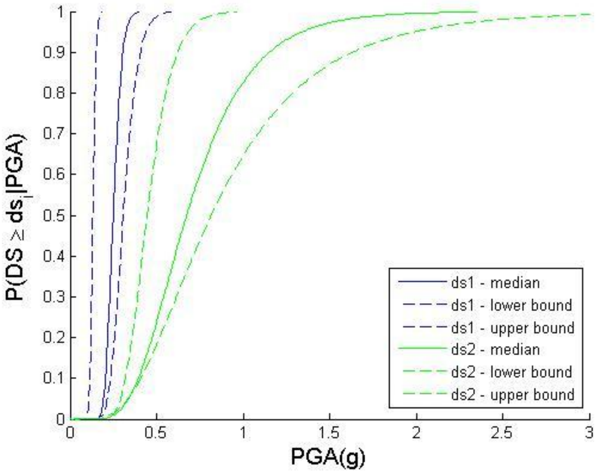


Figure 5. Example bridge fragility curves (ds1, ds2) for bridge type 1

Fragility curves were also assigned to road sections built on slopes of greater than 10 degrees to characterise the structural vulnerability of the road pavement to earthquake-triggered landslides. To do so, a methodology was adopted [24] that uses existing fragility curves for roads due to earthquake-triggered landslides [25] and represented in terms of PGA [26]. The fragility curves assigned to road sections were dependant on the road type (i.e. major or urban) and the associated $k_y$ value, and were represented in terms of three damage states: 1) Slight, 2) Moderate and 3) Extensive (Figure 6).

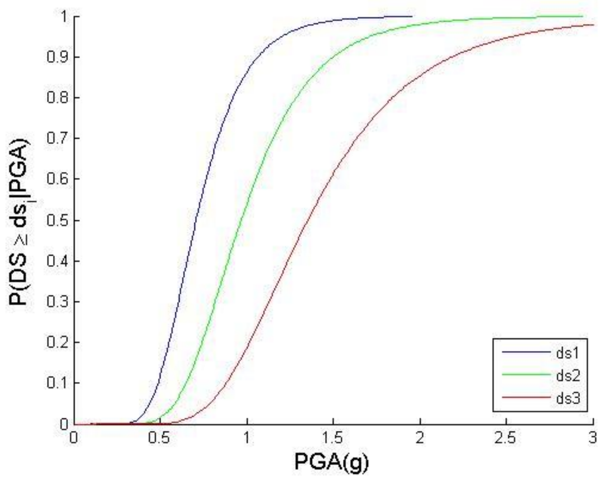


Figure 6. Example road fragility curves for urban roads ($k_y$=0.2)

The potential repair cost for the road network due to the associated hazards was estimated based on the individual network elements. To do so, the damage states defined for the network elements were directly related to a repair cost (Table 1) based on a survey that was distributed to infrastructure managers and experts within the INFRARISK consortium [21].

Table 1. Network direct consequences.

| | Repair Costs (€1000s) | | |
|---|---|---|---|
| Damage State | Bridges | Tunnels | Road Sections (per km) |
| Slight/Minor | 100 | 150 | 50 |
| Moderate | 750 | 1000 | 100 |
| Extensive | 1000 | 3000 | 350 |
| Complete | 1000 | 10000 | - |

### 4.5 *Risk Estimation*

To estimate the risk to the road network due to the earthquake scenario considered, a probabilistic analysis was performed according to a MCS method using random sampling, for which 1000 simulation loops were performed. Figure 7 illustrates a single sample of damage to the road network. For each network damage sample, the direct consequences were evaluated according to the total repair cost for the network.

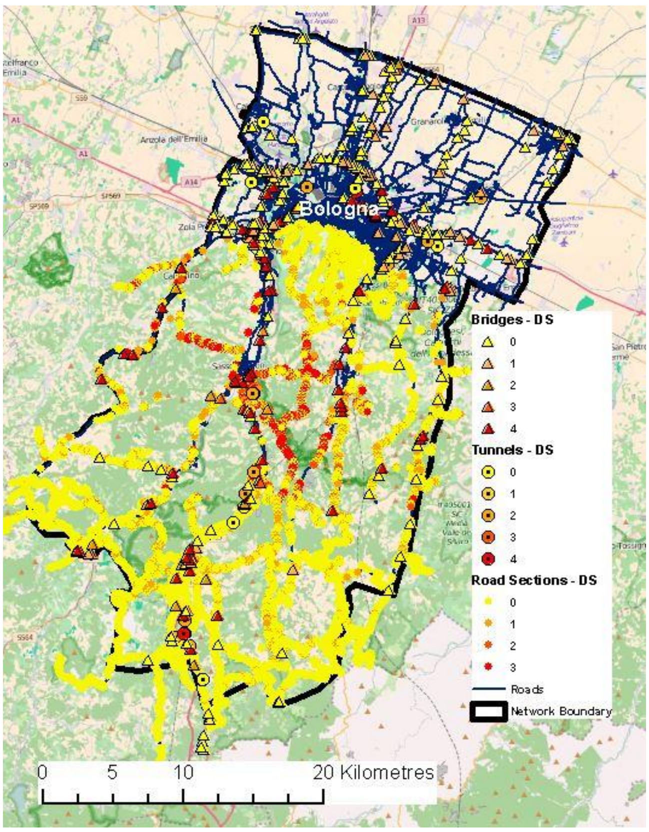


Figure 7. Network damage sample

## 5 RESULTS

To assess the convergence of the solution, the coefficient of variation (CoV) of the total repair cost was analysed according to the number of MCS loops, as illustrated in Figure 8. The solution converged to less than 1% after 200 simulation loops.

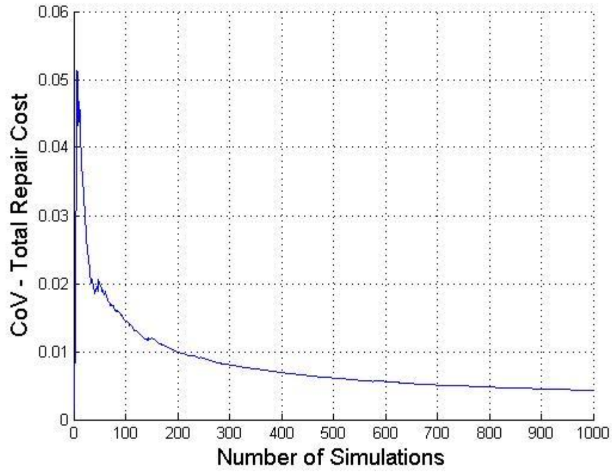


Figure 8. Convergence of solution

The evolution of the mean, μ, and the standard deviation, σ, for the network element repair costs (i.e. bridges, tunnels and roads) are illustrated in Figure 9. The potential damage to the network roads due to earthquake-triggered landslides contributed most significantly to the total potential repair costs for the network for the seismic hazard scenario considered.

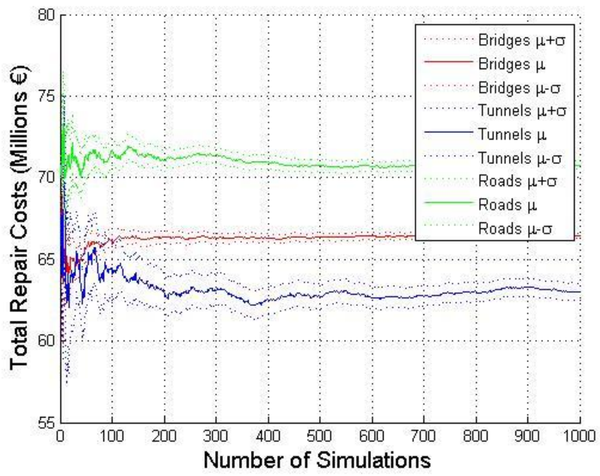


Figure 9. Network element repair costs (μ and σ) according to number of simulation loops

The exceedance probability in terms of the total repair cost for the road network due to the low probability, extreme seismic hazard scenario considered is illustrated in Figure 10. The results demonstrate that the total repair costs for the road network will most certainly exceed €140million for the scenario considered and, furthermore, there is a 50% chance that the total repair costs will exceed €193million. In addition to the monetary losses presented herein, there are indirect consequences due to the hazard scenario resulting from the additional travel times encountered by road users as a result of the network disruption and the consequent economic losses. This is the subject of future work for the Italian road network presented herein.

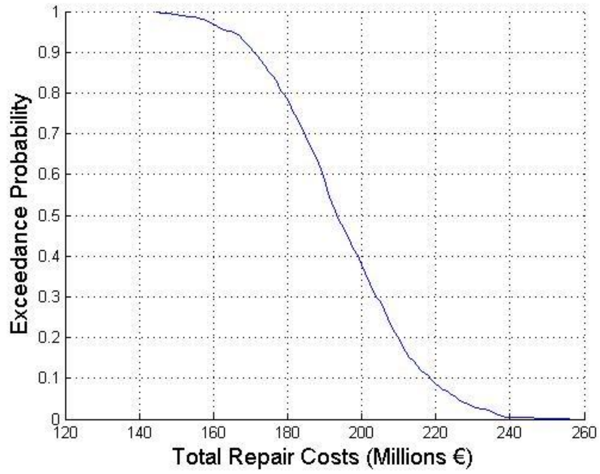


Figure 10. Total repair cost of network

## 6 CONCLUSION

This paper has presented the initial results of a risk assessment for a critical infrastructure road network due to an extreme seismic hazard scenario and the associated landslide cascading effects. The objective of the case study presented herein is to demonstrate the systematic application of the methodologies developed in the INFRARISK project.

Initial results have been presented for an Italian road network, which relate to the direct consequences associated with an extreme seismic hazard scenario. The associated repair costs are significant and this risk estimate may be considered as part of a broader stress testing framework for to determine whether or not the level of risk is acceptable and, furthermore, to assist in the decision making process with regard to the protection of this critical road network.

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